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# Simulation and comparison of the pressure profile of fumigated and non-fumigated polymer melts

*Martin Langlotz, Michael Koch*

Technische Universität Ilmenau, Fachgebiet Kunststofftechnik, Germany

## ABSTRACT

The production of various polymer foams is widely used for several years. In the automotive and packaging industries, these are more and more applications. There are various methods for preparing plastic foams. The properties of the foam may be achieved by using different influencing parameters, such as the manufacturing process conditions or the choice of the plastic material grade.
The processing and design of a single screw extruder (SSE) can be simulated by a simulation program based on fundamental analytical models or by FEM calculation methods for a particular purpose. In order to obtain meaningful results, assumptions have to be made for process parameters and screw geometry, however most importantly; the rheological properties of the material are a prerequisite. However, the rheological properties of a fumigated melt during the extrusion are unknown and have to be evaluated in appropriate experiments.
For the solution of the problem pressure profiles are recorded during the process in a screw from the point of gas inlet to extruder outlet thus representing the complete foaming process. These pressure profiles will be used for the validation of a simulation, which describes a fumigated melt. A comparison between fumigated and regular melt is executed and will be discussed in this paper.
The objective is to describe the rheological properties of the material using a pressure profile of a fumigated melt flow process.

## 1. INTRODUCTION

The viscosity of a thermoplastic melt gives a statement about the flow behavior of the plastic. Depending on the manufacturing process the product materials are selected with different viscosity. For the design of processing screws for fumigated materials, the viscosity of these plastic gas mixtures needs to be measured. To determine the viscosity of fumigated plastic requires high measuring expenditure and costs [1]. This paper will discuss a method based on a SSE and a mathematical model.

In Figure 1 the general process of the foaming process are shown. A two phase system is created when a polymer and a blowing agent (BA) as a gas are mixed. The BA diffuses over the surface of the plastic melt in the melt and resulting in a single-phase system under pressure. The nucleation and the volume expansion starts as soon as the melt exposed a pressure drop. This growth takes place until the blowing agent loaded polymer melt (BALPM) is stabilized.

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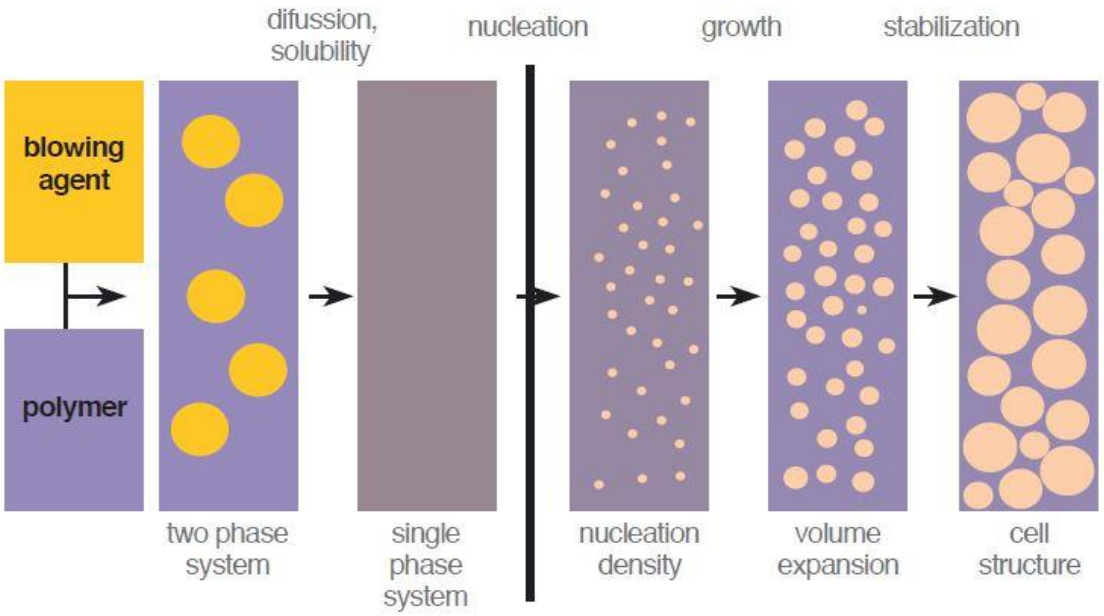


*Figure 1:* ***overall foaming process [2]***

This foaming process takes place in the processing machines, which are different depending on the procedure. Figure 2 shows for example a tandem extrusion system, as used for foam extrusion. In the primary extruder the plastic and all additives are melted and homogenized. After this the BA is added to the melt. The secondary extruder is used for cooling the BALPM. While the plastic is forced out of the die the cell growth and the volume expansion start, because of the pressure drop. In order to prevent collapsing and damaging the cells during the cell growth a high melt strength is needed. This melt strength increases with higher viscosity. Therefore cooling is necessary to increase the viscosity of the BALPM. This takes place in the secondary extruder.

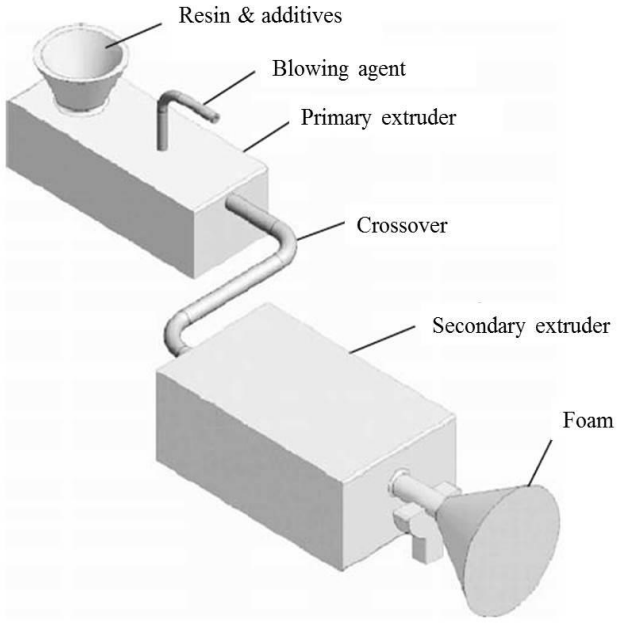


*Figure 2:* ***tandem extrusion system [3]***

## 2. RHEOLOGY OF BLOWING AGENT LOADED POLYMER MELTS

In BALPM the BA acts as a plasticizer; it has a viscosity-lowering effect on the melt. In Figure 3 a study of Polydimethysiloxan with $CO_2$ as BA and different weight percentage of the BA is shown [4]. These viscosity curves were recorded at the same temperature. In the left diagram the viscosity lowering influence of the BA on the viscosity can be seen. With increasing proportion of the BA, the viscosity decreases. These degrees of viscosity reduction depend on the choice of the matrix material and the BA. The viscosity curves were combined into a master curve using a shift factor $a_c$, which resulted from the measurements and was derived in the work of GERHARDT [4]. In the right part of Figure 3 this shows that the logarithmic gradient in the shear thinning range is relatively constant.

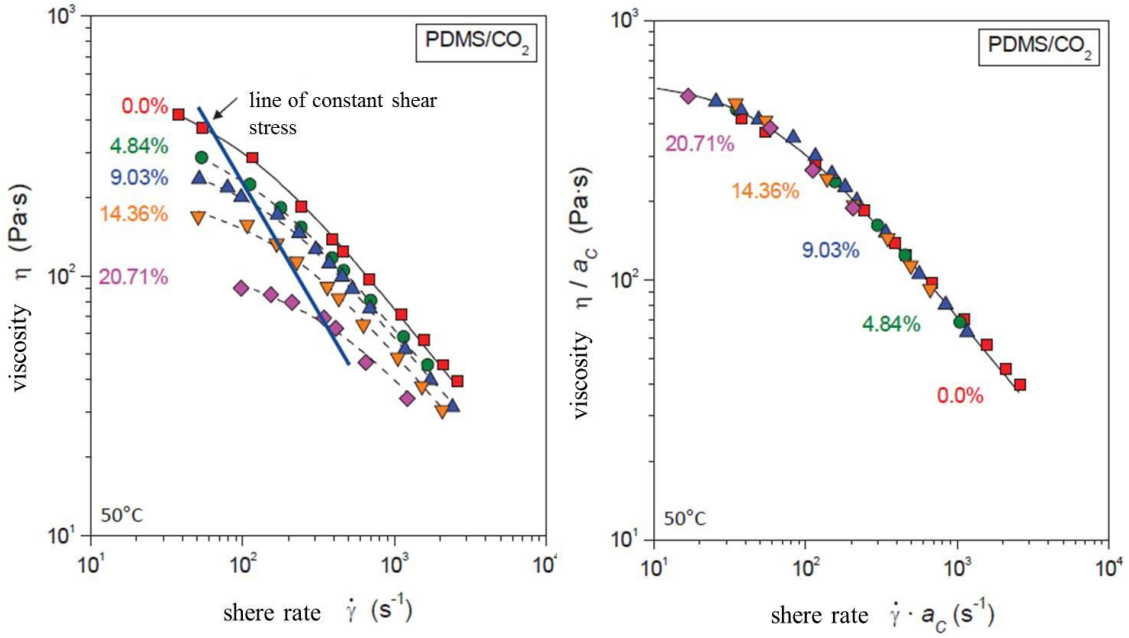


*Figure 3:* ***foaming agent influence on viscosity [1;4]***

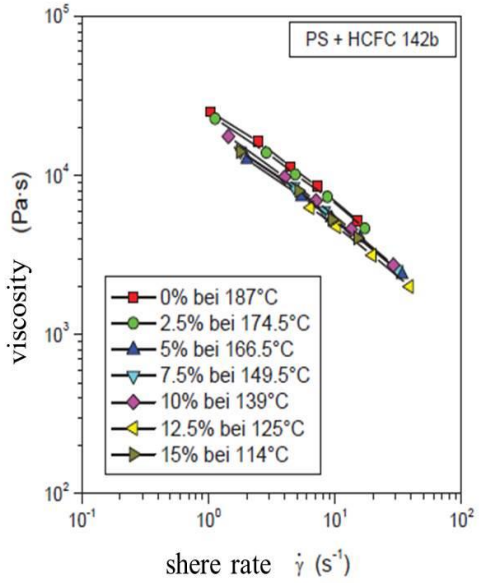


*Figure 4:* ***Viscosity of PS with HCFC 142b as BA; for different BA percentage and melt temperatures yielding similar viscosities [1;5]***

A high viscosity is desired for optimum cell growth. To counteract the effect of viscosity reduction, the plastic gas mixture can be cooled. This is shown in Figure 4. The analysis was conducted by GENDRON [5] in which the viscosity of the PS HCFC 142b increased by cooling. For example must the BALPM are cooled by 48 K in comparison between pure PS and PS with 10 percentage BA, to reach the same viscosity.

There are several possibilities to determine the flow behavior of BALPM. A method which often used in extrusion is the in-line rheometer [6]. Wherein a rheometer, with a round or slit die is connected to a foam extrusion line and the viscosity can be measured.
To measure the viscosity of a gas loaded melt, GERHARD [4] used a modified capillary rheometer. In this, a pressurized BA can add to the melt. This rheometer is sealed and has a back-pressure device. With this construction, it is possible to adjust shear rates which are far higher than that of the foam extrusion and to measure the viscosity.
RAPS [7] has determined the viscosity with a pressure cell. Here, a unit has been built on a rotational rheometer and measured the viscosity of high melt strength polypropylene with $CO_2$.

## 3. MATHEMATICAL MODEL

These above-mentioned measurement methods are based on the measurement of a pressure difference in a known channel geometry and under known process conditions. In order to avoid modifications of rheological measuring equipment the rheological material data which are should be determined by in-line pressure measurements along the screw. The new mathematical model for calculating the BALPM viscosity uses known models for the pressure/throughput behavior of SSE [8]. With these models pressure gradients along the screw can be calculated by using viscosity, channel geometry and extrusion process data. These models use the power law model to describe the viscosity $\eta$. [9]

$$\eta = K \cdot \dot{\gamma}^{n-1} \tag{1}$$

With the coefficient of power law K, The exponent of power law n and the share rate $\dot{\gamma}$.

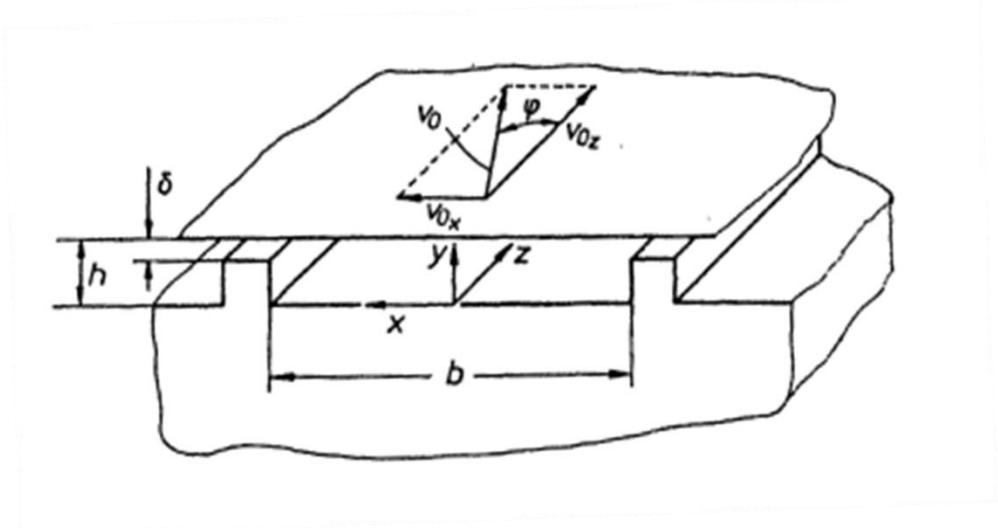


*Figure 5:* ***Channel model; with the channel depth h, channel width b, gab height δ, flight lead angle φ, velocity components $v_0$, $v_{0x}$ and $v_{0z}$ and the coordinates of the Cartesian coordinate system x, y and z. [8]***

For all calculations the Kinematic reversal and Cartesian coordinates are used. The denotation for the screw geometry is shown in Figure 5. Condition of use is that b>>h and the speeds in y-direction can be neglected. The velocity components $v_{0x}$ and $v_{0z}$ are given as [8]:

$$v_{0x} = v_0 \cdot \sin\varphi \tag{2}$$

$$v_{0z} = v_0 \cdot \cos\varphi \tag{3}$$

With the circumferential velocity of the SSE $v_o$ and the flight lead angle of the plastics processing screw φ.

The following assumptions are used for the calculations. The calculations refer to a range in which a constant channel depth $h_1$ is present. Furthermore, it is assumed that the channel is completely filled with melt with a constant melt temperature. For the isothermal case POTENTE [8] gives the following dimensionless relation:

$$\pi_{\dot{m}} = \phi_1 - \phi_2 \cdot \pi_p \tag{4}$$

With the nondimensional mass flow $\pi_{\dot{m}}$, the nondimensional pressure difference $\pi_p$ and the cross-flow units $\phi_1$ and $\phi_2$.

The cross-flow units $\phi_1$and $\phi_2$ are defined as [8]:

$$\phi_1 = \frac{n^{0,94} \cdot (2 - \cos\varphi) - \cos^{n-1}\varphi + \cos^n\varphi}{n^{0,94}} \tag{5}$$

$$\phi_2 = \cos^{n-1}\varphi \tag{6}$$

The nondimensional mass flow $\pi_{\dot{m}}$ is given as [8]:

$$\pi_{\dot{m}} = \frac{2 \cdot \dot{m}}{\rho_1 \cdot b_1 \cdot h_1 \cdot v_{0z}} \tag{7}$$

With the mass flow rate ṁ, the melt density ρ, the width in the metering zone $b_1$ and the channel depth in the metering $h_1$ and the circumferential velocity in the channel direction.

And for the nondimensional pressure difference $\pi_p$ applies [8]:

$$\pi_p = \frac{\Delta p \cdot h_1^{1+n}}{6 \cdot n^{0,94} \cdot K \cdot v_{0z}^n \cdot Z} \tag{8}$$

With the pressure difference Δp between the measuring points and the distance between the measuring points Z. Substituting equation 7-8 in equation 4 results in the following expression.

$$\frac{2 \cdot \dot{m}}{\rho_1 \cdot b_1 \cdot h_1 \cdot v_{Oz}} = \phi_1 - \phi_2 \cdot \frac{\Delta p \cdot h_1^{1+n}}{6 \cdot n^{0,94} \cdot K \cdot v_{0z}^n \cdot Z} \tag{9}$$

Equation 9 can be written as:

$$K = \frac{{h_1}^{1+n} \cdot \Delta p}{6 \cdot v_{0z}^{n} \cdot Z \cdot \left( \frac{-\frac{2 \cdot \dot{m}}{\rho \cdot b \cdot h_1 \cdot v_{0z}} + \phi_1}{\phi_2} \right)} \tag{10}$$

For a determination of the viscosity parameter now two possibilities will be presented.

### 3.1 Calculation using a known exponent of power law

For this calculation, following assumption is made. The exponent of power law n is the same for fumigated and non-fumigated polymer melts constant, as this was confirmed in the work of GERHARDT [4]. Thus a known n (e.g. from rheometer measurements) can be used for the calculation of the coefficient of power law K with equation 10.
The acting shear rate is given as [8]:

$$\dot{\gamma} = \frac{v_{0z}}{h_1} \tag{11}$$

It is possible for several operating points of the SSE to set various shear rates by changing $v_0$; and record a range of the viscosity curve. For each operating point also used the circumferential speed, the measured differential pressure and the mass flow rate of the polymer melt need to be known.

### 3.2 Calculation without a known exponent of power law

With the assumption that no known n is used and that n and K for two operating points are the same:

$$\frac{{h_1}^{1+n} \cdot \Delta p_I}{6 \cdot v_{0z}^{n} \cdot Z \cdot \left( \frac{-\frac{2 \cdot \dot{m}_I}{\rho \cdot b \cdot h_1 \cdot v_{0z_I}} + \phi_1}{\phi_2} \right)} = \frac{{h_1}^{1+n} \cdot \Delta p_{II}}{6 \cdot v_{0z}^{n} \cdot Z \cdot \left( \frac{-\frac{2 \cdot \dot{m}_{II}}{\rho \cdot b \cdot h_1 \cdot v_{0z_{II}}} + \phi_1}{\phi_2} \right)} \tag{12}$$

In this case, the operating point I and II, differ in the circumferential speed, in the measured pressure differential between the two measurement points and the determined mass flow rate.
A solution to this equation yields the exponent of power law n. The coefficient of power law K can be determined with using equation 10.

The material parameters can be calculated for several shear rate ranges by starting multiple operating points, during setting different speeds, measuring the respective pressure differences and measurement of mass flow of the extruded plastic material.

## 4. EXPERIMENTAL SETUP AND VERIFICATION OPTIONS

A schematic structure of the laboratory SSE is shown in Figure 5. It has a diameter D = 45mm and provides several sensors, with which the cylinder wall temperature and the pressure along the screw can be recorded. Before the extrusion die, the bulk temperature of the melt is determined by a sword sensor.

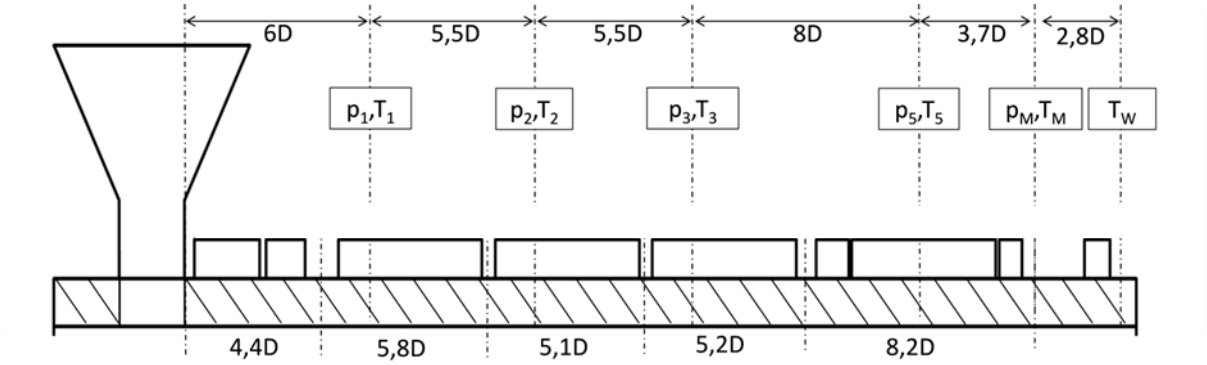


*Figure 6:* ***Single screw extruder (D=45mm) with several sensors***

For multiple preset circumferential speeds an area of the flow curve can be calculated. This viscosity curve can be compared for non-fumigated melts with standard rheometer measurements; in order to determine the accuracy of the calculation methods presented in this paper. In this manor will be inaccuracies are identified and corrected. It is also possible to obtain a comparison between the viscosity behavior of fumigated and non-fumigated melt.
Using the determined viscosity of BALPM extrusion lines can be efficiently designed for a specific foaming process.

## 5. CONCLUSIONS

A way to determine the viscosity of fumigated and non-fumigated melting was presented, which uses fundamental mathematical models for the processing of plastic melts in SSE. Hence additional modified measuring devices are not required.

## NOMENCLATURE

| | |
|---|---|
| $a_c$ | Shift factor |
| $b_1$ | Channel width |
| D | Screw diameter |
| $h_1$ | Chanel depth of metering stage |
| K | Coefficient of power law |
| $L_M$ | Metering zone length |
| L | Total effective screw length |
| $\dot{m}$ | Mass flow |
| n | Exponent of power law |
| $p_{1\text{-}5,M}$ | Pressure at measuring point 1-5 or melt |
| $T_{1\text{-}5,M}$ | Temperature at measuring point 1-5 or melt |
| $v_0$ | Circumferential speed |
| $v_{0x}$ | Circumferential speed in x-direction |
| $v_{0z}$ | Circumferential speed in screw channel direction |
| Z | Total effective length of the screw flight |

| | |
|---|---|
| $\dot{\gamma}$ | Share rate |
| $\Delta p$ | Pressure difference |
| $\eta$ | Viscosity |
| $\pi_{\dot{m}}$ | Nondimensional mass flow |
| $\pi_p$ | Nondimensional pressure difference |
| $\rho$ | Density of melt |
| $\varphi$ | Flight lead angle |
| $\phi_1$; $\phi_2$ | Nondimensional cross-flow units |

**Indices**

| | |
|---|---|
| I | operating point 1 |
| II | operating point 2 |

**ABBREVIATION**

| | |
|---|---|
| BA | Blowing agent |
| BALPM | Blowing agent loaded polymer melts |
| SSE | Single screw extruder |

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**CONTACTS**


M. Sc. Martin Langlotz martin.langlotz@tu-ilmenau.de
Univ.-Prof. Dr.-Ing. Michael Koch michael.koch@tu-ilmenau.de